AN ISSUE OF PERMANENCE: ASSESSING THE EFFECTIVENESS OF TEMPORARY CARBON STORAGE

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Abstract

In this paper, we present a method to quantify the effectiveness of carbon mitigation options taking into account the "permanence" of the emissions reduction. While the issue of permanence is most commonly associated with a "leaky" carbon sequestration reservoir, we argue that this is an issue that applies to just about all carbon mitigation options. The appropriate formulation of this problem is to ask 'what is the value of temporary storage?' Valuing temporary storage can be represented as a familiar economic problem, with explicitly stated assumptions about carbon prices and the discount rate. To illustrate the methodology, we calculate the sequestration effectiveness for injecting CO_2 at various depths in the ocean. Analysis is performed for three limiting carbon price assumptions: constant carbon prices (assumes constant marginal damages), carbon prices rise at the discount rate (assumes efficient allocation of a cumulative emissions cap without a backstop technology), and carbon prices first rise at the discount rate but become constant after a given time (assumes introduction of a backstop technology). Our results show that the value of relatively deep ocean carbon sequestration can be nearly equivalent to permanent sequestration if marginal damages (i.e., carbon prices) remain constant or if there is a backstop technology that caps the abatement cost in the not too distant future. On the other hand, if climate damages are such as to require a fixed cumulative emissions limit and there is no backstop, then a storage option with even very slow leakage has limited value relative to a permanent storage option.

Introduction

Management of greenhouse gases using carbon sequestration technologies (Herzog *et al*., 2000; Herzog, 2001) is being proposed to complement mitigation strategies that improve energy efficiency or increase the use of non-fossil energy sources. Reichle (1999) defines carbon sequestration "as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere." Reservoirs to provide for the storage of carbon include underground geologic formations, trees and soils, and the deep ocean. However, these reservoirs are not necessarily permanent. This poses the challenge of how to quantify the benefits of temporary carbon storage, for example on the time-scales of decades or centuries.

The issue of permanence is currently being hotly debated, primarily as it applies to carbon sequestration in trees and soils (Marland *et al.*, 2001). In this paper, we propose a methodology, based on fundamental economic principals, to quantify the benefits of carbon sequestration in a non-permanent reservoir. We then define "sequestration effectiveness" as the ratio of the benefit gained from temporary storage compared to the benefit gained if the storage was permanent. This method is applied to an ocean carbon sequestration example, but can just as easily be applied to other storage reservoirs, such as trees and soils or even currently unused fossil reserves in the ground.

Background

The Issue of Permanence

Most attention to the issue of permanence has been on biological sequestration (Noble *et al.*, 2000), but many of the same concepts are directly applicable to the issue of ocean sequestration. In both cases, carbon is either removed from or kept out of the atmosphere, but some or all of it may ultimately return to the atmosphere. This has contributed to the idea that one ought to pay a lower price for sequestered carbon compared to the price paid for "avoiding" carbon emissions in the first place (termed "avoided emissions" in this paper). For example, in its simplest form, if a ton of carbon is sequestered with one-half leaking into the atmosphere over time, then as a first approximation the value of sequestering a ton of carbon should be one-half the value of a ton of avoided emissions. Unfortunately, the situation is much more complex than suggested by this simple example.

The first complexity deals with defining avoided emissions. Conventional wisdom associates avoided emissions with reduced use of fossil fuels (e.g., from improving energy efficiencies, increasing conservation, shifting to non-fossil energy sources, etc). It is argued that if a ton of fossil fuel is not used, its emissions are avoided forever. However, as pointed out by Noble *et al.* (2000), the idea that a ton of fossil emissions avoided today is avoided forever is not necessarily an accurate characterization of the problem because that unburned fossil fuel may still be mined and burned later. In fact, economic considerations lead one to conclude that a ton of avoided emissions today will, absent an absolute quantity constraint on emissions in all regions through time, mean higher emissions in the future. The simple reasoning is that the price path of fossil fuel will be lower in the future because these inexpensive resources still exist and therefore the future use of fossil fuels and carbon emissions would increase. Thus, there will be leakage into the future from avoided emissions that is analogous to the leakage of carbon from sequestration reservoirs. The temporal leakage from a carbon policy is analogous to well recognized spatial leakage that occurs when only part of the world undertakes a carbon policy. In other words, the idea that avoided fossil fuel emissions today are avoided forever is in error.

Further complicating the issue is the realization that there may be value to having carbon temporarily removed from the atmosphere. For example, Wigley *et al.* (1996) make several cases for the value of delaying fossil emissions reductions, including the value of avoiding premature capital stock retirement, the time value of money (economic discounting), and the possibility of technological developments that will make fossil fuel alternatives cheaper. Any of these cases for delay of fossil fuel emissions reductions can also be seen as a case for temporary sequestration; rather than accept the higher concentrations and damages that would result from delay in emissions reductions one can avoid them through sequestration offsets even if they are only temporary.

Ton-year Accounting

Attempts to value temporary storage has led many analysts to propose a ton-year accounting approach where carbon sequestration is valued on the basis of both the number of tons sequestered and years over which it is sequestered (Noble *et al.*, 2000). While there are many different formulations of the ton-year approach, most have artificially truncated the time horizon. A common assumption is to assume that storage of 100 years or more is permanent storage and therefore equivalent to a reduction in fossil fuel emissions. Storage of less than 100 years (say T years) would be credited less. The "discount" for non permanent storage is based on difference in the integrated atmospheric carbon over the 100 years from a pulse of carbon removed from the atmosphere at time t=0 and re-emitted to the atmosphere at time t=T based on a simulation of a carbon cycle model. The rationale for the 100-year horizon is based on the argument that the problem of comparing carbon storage of different lifetimes is conceptually equivalent to comparing greenhouse gases of different lifetimes. This comparison has already been addressed by the construction of Global Warming Potential indices (GWPs), with those adopted in the Kyoto Protocol based on 100-year horizons. However, many have pointed out that the GWPs lack any fundamental economic (or other) rationale and that their application can have undesirable consequences (Schmalensee, 1993; Eckaus, 1993; Reilly and Richards, 1993; Kandlikar, 1995, 1996; Reilly *et al.* 1999; Manne and Richels, 2001; Reilly *et al.*, 2001a), thus this line of argument offers weak support for the ton-year idea if it does not damn the formulation outright.

The peculiarity of this ton-year concept is that the value of temporary storage is completely determined by the choice of the time horizon that is considered to be permanent. A short horizon will make temporary storage valuable while a long horizon will give little value to it. There is no connection to underlying economic conditions that would determine a carbon price and no other basis provided for choosing 100 years or any other horizon length. Indeed, deep ocean storage is essentially permanent if 100 years is adopted as the horizon in a ton-year approach. As far as the topic of this paper is concerned, adopting the ton-year convention with a 100-year horizon would lead one to conclude that ocean sequestration is equivalent to avoided emissions. As the ton-year formulation has its roots in the GWP formulation it is not surprising that a similarly perverse result is obtained for estimating GWPs for the very long-lived (1000s of years) greenhouse gases. The 100-year GWPs consider only the radiative effects of the first 100 years of gases like SF_6 and CF_4 and thus completely ignore the radiative effects over the remaining lifetimes of 3100 and 49,900 years respectively. Short-lived versus long-lived greenhouse gases and short-term and long-term temporary storage thus face similarly asymmetric treatment in these formulations.

An Economic Approach

Noble *et al.* (2000) also review what is, in our view, the simplest and the correct management approach for sequestration. They refer to the approach as treating removals and emissions as separate events. The idea is that when one removes a ton of carbon, one receives the going price of carbon. When a ton of carbon is released the owner of this carbon must then purchase a credit from elsewhere at the going price. The purchase will in turn lead to one less ton of net emissions elsewhere. This approach reinforces the idea that sequestration is, in fact, no different than avoided emissions. If one avoids a ton of emissions in year one, a credit is earned that can be sold. If one turns around and emits an extra ton of carbon next year, then one must buy a credit at the prevailing price and that means that someone else must reduce emissions by the extra ton. As with production of all other commodities in the economy, those who make long-lived investments (such as planting a tree or installing carbon removal equipment) must make an estimate of the likely price path of the good they are producing (emissions reduction/carbon sequestration) and compare the rate of return on that investment with other ways to invest the money. A calculation based on the expected price path of carbon and alternative rates of return must be made when an investment is considered. Any particular investor's expectations may prove to be wrong, and then there will be capital gains or capital losses. But the chance, and indeed likelihood, of being wrong does not mean that one should not use one's best estimate of the future price path at the time an investment is made. A key element of this approach is that carbon, once sequestered, creates a permanent liability for the owner. Here there may be some differences between ocean and geologic or terrestrial storage. It is not, in principle, difficult to associate a permanent liability with a plot of land or a geologic reservoir, monitor the carbon and insure that the owner and succeeding owners have credits to cover any release whether due to natural conditions or changed management of the sequestered carbon. However, with ocean sequestration it is not practical to determine specific liability for carbon returning from the ocean to the atmosphere when some of the carbon has been naturally taken up by the ocean while other carbon may have been intentionally sequestered by any number of different firms or agents.

Carbon Prices and the Discount Rate

A major rationale for the schemes such as the ton-year approach is that they can be calculated without an explicit price path or discount rate. Proponents see these economic variables as particularly uncertain and speculative. Yet, avoiding an explicit treatment of these economic variables means that the choice of other values implies particular and sometimes peculiar values for economic variables. For example, Reilly and Richards (1993) show that the 100-year time horizon is equivalent to assuming constant marginal cost damages, a discount rate of zero for the first 100 years and a discount rate of infinity thereafter. Reilly *et al.* (2001a) point to the further peculiarity of this assumption in that recent economic work has suggested that a declining discount rate should be used for very long term problems whereas the GWP formulation assumes the extreme opposite, with a dramatically higher discount rate for the very long term.

We confront the issue of the long-term value of carbon storage and the discount rate directly as these are values, that while admittedly highly uncertain, where one can appeal to an underlying rationale. The mathematical formulation is presented in the next section. For the ocean sequestration problem, we must concern ourselves with hundreds and thousands of years and we thus require some relatively simple but powerful assumptions. In this regard, the next section also formulates the future price path of carbon based on three such rationales.

Calculating Sequestration Effectiveness

Mathematical Formulation

The net present value (NPV) of the benefits of a carbon sequestration strategy can be calculated as follows:

$$NPV = \int_0^\infty p(t)A(t)e^{-rt}dt \tag{1}$$

where p is the carbon price (\$/tonne), A is the abatement or avoided emissions (tonnes/yr), r is the discount rate (/yr), and t is the time (yr). Note that if carbon emissions are removed from the atmosphere, $A(t)$ is positive and a positive economic benefit (credit) results. If carbon leaks from the storage reservoir into the atmosphere, $A(t)$ is negative and a negative economic benefit (debit) results. The carbon price may change over time, so if carbon is removed from the atmosphere when prices are high and it leaks back in when prices are low, the sequestration can still have a net economic positive benefit.

To evaluate equation 1, assumptions must be made about both a carbon price and a discount rate. It is important to note that no matter what methodology one uses, this information is always required to evaluate mitigation economics over time. However, in many methods, these assumptions are hidden because they are made implicitly. The ton-year approach implicitly assumes carbon prices that are constant over time and that the correct discount rate is 0%, at least up to the artificially truncated horizon of 100 years.

Equation 1 can also be approximated as a summation as follows:

$$NPV = \sum_0^\infty p(t)a(t)(1+r)^{-t} \tag{2}$$

where $a(t)$ is now the amount of carbon flowing into the sequestration reservoir for a given time interval (note that if the net carbon flow is out of the reservoir, then $a(t)$ is negative).

The sequestration effectiveness (h) is defined as the ratio of the net benefit gained from temporary storage compared to the benefit gained if the storage was permanent. A sequestration effectiveness of 100% corresponds to permanent storage, while one of 0% has absolutely no benefit. Note that to fully judge whether a sequestration strategy is worthwhile, costs must also be considered. For example, it is more economical to pursue an option with a sequestration efficiency of 50% if it costs less than half (in terms of \$/tonne) of a permanent sequestration option. Equations 1 and 2 can easily be modified to include sequestration costs as well as benefits. However, examining sequestration costs is beyond the scope of this paper.

For the case of where a_o tonnes of CO_2 are sequestered at t=0 and there are no leaks over time (i.e., permanent sequestration), equation 2 reduces to $p_o a_o$. If this reservoir leaks over time, the sequestration effectiveness can then be calculated as follows:

$$h = \frac{\sum_{0}^{\infty} p(t)a(t)(1+r)^{-t}}{p_o a_o} \tag{3}$$

Carbon Prices Over Time

A critical element of equation 3 is the carbon price. We describe three cases in terms of the price path, independent of the specific level of price, and show that in each case, the absolute level of price drops out of the comparison of *relative* effectiveness of temporary as compared with permanent storage. Thus, the formulation describing the relative value of the different options does not depend on whether one believes the current price of carbon should be very high or very low but instead on characteristics of the price path. In this regard, we choose two extreme cases that bracket possible future price paths (constant price and exponential increase), and an intermediate case (exponential increase for some period and constant thereafter). Casual interpretation might imagine that the exponential price case is a high price case, but the constant price case could be a very high price, and the initial value of the exponential price very low such that it would be hundreds or thousands of years before the exponential price exceeded the constant price. We appeal to traditional cost-benefit analysis to justify these different paths but, because the level of the price drops out of the final equation, we make no particular assumption about the specific methods used to value damages, or how damages to different groups are weighted.[1]

More critical to this formulation is the assumption of cost-effectiveness—i.e. that however the goal of a carbon mitigation policy is developed, it is achieved cost-effectively by equilibrating carbon price across options and comparing options across time by considering the time value of funds—i.e. using a discount rate. Perhaps the most troubling aspect of the management of very long term problems such as climate change is that it requires an institutional commitment to pursue a policy indefinitely. The reasoning we use to justify these different paths implicitly requires such commitment. Specifically, this formulation implies that, over the hundreds and even thousands of years over which carbon may leak out of a reservoir, an institution like the Framework Convention on Climate Change (FCCC) and the governments that support it remain in place or are succeeded by similar institutions that maintain a commitment to manage atmospheric carbon as described by these cases. Given the inability of at least some of the current governments (notably the United States) to agree even to the Kyoto Protocol this assumption may seem farfetched at best. In the case of long-term (but temporary) storage of carbon through ocean sequestration, for example, we are implicitly assuming that as the carbon is

[1] For example, a view that endangering some set of small island states is a catastrophic loss that could not be compensated is completely consistent with our model as long as one can describe a concentration of GHGs that would avoid the loss. In this case, one need not appeal to monetary valuation of damages or necessarily rely on a Pareto optimality that relies on the assumption that losers from the policy are compensated.

gradually returned to the atmosphere over thousands of years that an FCCC-like institution enforces a carbon policy that offsets this leakage back to the atmosphere.[2]

Whether it is possible to insure an intergenerational commitment of the type required to manage climate change has been the subject of considerable analysis and discussion with regard to the applicability of discounting to the climate problem (Lind and Schuler, 1998) and its equity implications among generations. In our case of sequestration, a current, or intervening, generation might pursue sequestration in leaky reservoirs realizing that only future generations would bear the extra costs associated with the leakage and these future generations have no way to go back and make the earlier generations pay. Obtaining efficiency, and equity, requires that each generation respects the long-term carbon management plan and operate without shirking its responsibility. As described in Lind and Schuler (1998) some have proposed that a bond be posted as some form of insurance should a generation shirk but there is no way to prevent an intervening generation from rewriting the rules and cashing in the bond other than trusting them to be fair. But, the bond is necessary only because one did not trust them in the first place, and so it offers no additional protection.

The problem of intergenerational commitment reemphasizes our earlier point that avoided emissions, while considered 'permanent' are in fact not so. A shirking generation or two could go back to using fossil fuels without restraint, as long as they remain in the ground. Thus avoiding fossil fuel use now is a permanent reduction in concentrations only to the extent that we trust that all intervening future generations do not shirk. About the only way to avoid the potential to shirk is through technological solutions. One would be to invent alternatives to fossil fuels that are so much more desirable (e.g. dominates fossil fuels in all ways) that future generations have no reason to want to use them. A second would be to dig up all the fossil fuels, burn them, and permanently sequester the carbon in a form that would never be released to the atmosphere (e.g. calcium carbonate). Absent these rather extreme cases, the best our generation

[2] With an absolute concentration cap, a natural earth system that otherwise was in 'equilibrium' (zero net exchange of carbon between the atmosphere and other reservoirs) would require net negative emissions to offset this leakage. As pointed out by an anonymous reviewer, if the only option for managing atmospheric carbon were to reduce fossil fuel emissions then net negative emissions would not be possible. This boundary condition would appear to preclude the use of temporary storage and still maintain an absolute cap on concentrations. Existence of a technology that can remove carbon from the atmosphere in sufficient amounts to offset the leakage is one way to avoid this boundary condition. Retaining forest carbon sink potential for later periods, so that a further permanent managed increase in the forest carbon stock could be achieved through forestation, is one such technology that overcomes this boundary condition. This would place some strong limits on the quantity of sequestration in leaky reservoirs. Others (Dubey *et al.*, 2002) have suggested the technical feasibility, and even argued that it could be economically feasible, for removing carbon from the atmosphere using technology similar to that used to remove CO_2 from a smokestack. The carbon so removed could be permanently sequestering it as calcium carbonate, for example. This would be a backstop that could achieve indefinite net negative emissions. Even if such backstops are removed from consideration, an efficient solution might still indicate economic value in using some leaky storage now, to slow the rate of climate change. The economic rationale would be that temporary storage would then allow a more gradual and less costly adaptation of the economy and natural ecosystems. To be able to still meet the concentration target, it would then be necessary to keep cumulative emissions low enough so that, even after all of the ocean carbon leaked back to the atmosphere, the target concentration would be met. The addition of the temporary storage option provides added flexibility to jointly optimize both the economic costs of restructuring the economy and the time profile of climate damages. Again, management of carbon at this degree of precision over centuries raises the many issues associated with institutional stability and the inability to bind intervening generations to the long-term management plan.

can do is to operate in a responsible manner and trust that intervening generations will do the same. Given the institutional commitment to manage carbon over time, we can now analyze Equation 3 in terms of three different price paths.

Case 1 - Constant Carbon Prices

In this case, $p(t) = p_o$, which reduces equation 3 to:

$$h = \frac{\sum_0^\infty a(t)(1+r)^{-t}}{a_o} \tag{4}$$

This is a simple formulation that assumes there are constant *marginal* damages from increasing emissions of greenhouse gases.[3] With constant marginal damages the optimal price path is fully determined by the marginal damage. The carbon price is constant over time and equal to the marginal damage estimate. Any justification for this formulation is based more on lack of contrary evidence than clear evidence for constant marginal costs. Estimates of damages remain highly uncertain (Tol, 2001), but one feature of damage studies is that nearly all aggregate monetized damage estimates are based on impact studies using equilibrium doubled CO_2 climate scenarios (Reilly *et al*., 2001b; Nordhaus and Boyer, 2000). The single point estimate of damages does not provide degrees of freedom to estimate curvature of the damage function. Some literature assumes that the varying temperatures derived from different climate models under a CO_2 doubling can be used as if they were the simulated climates from a single climate model with varying concentration levels. Other work has used pure sensitivity analysis, arbitrarily varying temperature and precipitation in an impact model. This evidence has suggested to some analysts that damages may increase more than proportionally with temperature (Smith *et al.*, 2001). Emissions and temperature are, however, also non-linear as radiative forcing increases less than proportionally with concentrations changes because of saturation, as reviewed by Hansen *et al.* (2000). This non-linearity operates in the opposite direction, perhaps canceling to some degree the supposed non-linearity in damage and temperature.

Case 2 - Carbon Prices Increase at the Discount Rate

In this case, $p(t) = p_o (1+r)^t$, which reduces equation 3 to:

$$h = \frac{\sum_0^\infty a(t)}{a_o} \tag{5}$$

Note that mathematically, this scenario is equivalent to having constant prices, a 0% discount rate, and an infinite time horizon.

[3] With constant *marginal* damages, *total* damages will rise over time as concentrations increase.

This formulation views the additional carbon holding capacity of the atmosphere as a fixed resource that can be allocated over time. This conception of the problem is roughly consistent with the goal in Framework Convention on Climate Change of stabilizing concentrations of greenhouse gases. Given a stabilization target and assuming eventual long-run equilibrium is established with the terrestrial and ocean stocks, a concentration goal implies a fixed ceiling on cumulative emissions from fossil fuels over all time. The economic problem is to allocate the rights to these cumulative emissions over time. Hotelling (1931) demonstrated that under such conditions the price path for the resource would rise at the discount rate. The price for such a resource has since come to be known as a Hotelling rent.

Case 3 - Carbon Prices Increase at the Discount Rate for t Years, then Remain Constant*

In this case, sequestration effectiveness is calculated by equation 6:

$$h = \frac{\sum_{0}^{t^*} a(t) + \sum_{t^*}^{\infty} a(t)(1+r)^{-(t-t^*)}}{a_o} \qquad (6)$$

The rationale for this case is that there is an alternative non-fossil energy source that will place a cap on abatement costs. Often such a technology is referred to as a backstop technology, a term attributable to Nordhaus (1979) who showed that under such a case the price path will follow that of a Hotelling resource, rising at the discount rate, until it is capped by the backstop price. The assumption here is that a carbon-free energy backstop enters at time t^*, but at premium price over fossil energy. The owner of the leaking reservoir could indefinitely purchase permits at the backstop price to cover leakage.[4] In this case, the long-term price is set by the abatement cost independent of the damage cost. Many technologically based models of the global energy system assume one or more backstop technologies exist (Manne and Richels, 1995; Edmonds *et al.*, 1995). In these complex models an absolute cap may not be achieved for various reasons. The simplified price path we use captures the essence of this representation of the future.

[4] An anonymous reviewer questioned whether incentives to develop such a backstop would exist if 'quick fix' sequestration were being used. That is: Why would anyone develop such a backstop if it appeared that the problem was solved by ocean sequestration? The earlier discussion regarding intergenerational commitment provides the general answer to this question. In the specific case of the incentives to develop a backstop, we require that our responsible FCCC-like institution would credibly maintain its carbon management goal no matter what happened. Thus, failure to develop a backstop would lead to continued exponential escalation of the carbon price, making invention of the backstop ever more economically attractive. To get introduction of the backstop just as its price is competitive requires forward-looking agents. While an exact introduction at its marginal price would, in our view, be at best a rough approximation, it is the case that economic agents in markets appear to act in a forward-looking manner. For example, agents looking ahead to the predicted exhaustion of known fossil fuel deposits or toward expected limits on cultivable land have proved amazingly inventive such that, instead of rising prices for fuels and food as such limits would imply, the long term trend in real prices so far has been down for as far back as records can be constructed. The important difference with carbon management is that the constraint on emissions is not a physical given (as in the case of fuel resources and land) but must be imposed by an institution that might come under the control of a generation of shirkers.

Applying Sequestration Effectiveness to Ocean Carbon Sequestration

To illustrate the above methodology, we analyze carbon sequestration in the deep ocean. We chose this example because we can use a model to quantitatively predict the leakage rate over time and the storage time is on the order of centuries (as opposed to decades or millennia), which is probably the time period of most interest for temporary storage. Also, ocean carbon sequestration is currently being researched as a possible carbon mitigation technology.

Modeling a leaky ocean

In describing oceanic uptake of CO_2, one can state that more than 80% of the carbon injected into the atmosphere will end up in the ocean. It is equally true that over 80% of any CO_2 injected into the ocean will remain in the ocean. However, it can also be said that for certain locations, any injected CO_2 will leak out on a timescale of 300 years. In order to properly simulate this problem, it is important to understand how this superficially differing claim can be reconciled with the first two statements.

At the heart of the issue is separating "engineered" sequestration from "natural" sequestration. If we emit CO_2 to the atmosphere, natural cycles will eventually absorb approximately 80% of it into the ocean. If we inject the CO_2 into the ocean instead, all of it will eventually leak out (basis of the 300 year timescale), but most of it will eventually get reabsorbed by the ocean (claim that 80% remains in the ocean). If we were looking at leaks from a geologic reservoir, we would not take credit for the ocean absorption via natural cycles. Similarly, when judging the effectiveness of ocean reservoirs, we should not consider the reabsorption of CO_2 that has degassed to the atmosphere.

To correctly account for this effect in a model, one must choose an appropriate atmospheric CO_2 boundary condition. The model could be run with a specified atmospheric CO_2 concentration, where all of the injected CO_2 will have leaked back to the atmosphere in the steady state. Alternatively, it could be run with a responsive atmospheric CO_2 concentration that increases as the sequestered CO_2 outgasses, with about 80% of the injected CO_2 remaining in the ocean at steady state. We suggest that the specified atmospheric CO_2 boundary condition is the appropriate one for measuring the effectiveness of ocean sequestration strategies, because it does not credit ocean sequestration with the natural uptake of CO_2 from the atmosphere.

Simulation Model

A set of simulations of direct injection of CO_2 into the ocean using a one dimensional box-diffusion model (Caldeira *et al.*, 1998) were performed to calculate the rate at which the CO_2 outgases into the atmosphere over time. The model was run for a generic ocean site with injections at depths of 500, 1000, 1500, 2000, and 3000 meters.

In the model, the ocean is represented by a box-diffusion model (Oeschger *et al.*, 1975; Siegenthaler, 1983) with a 75 m thick mixed-layer and a total depth of 3800 m, as described by Caldeira *et al.* (1998). Ocean carbon chemistry (Stumm and Morgan, 1981) is calculated using a surface temperature of 18 °C, salinity of 35 psu, and alkalinity of 2.23 eq m^{-3}, with constants as specified in Roy *et al.* (1993), Dickson (1990), Millero (1995), and Weiss (1974). The eddy diffusion and gas-transfer velocity coefficients were chosen such that the change in ocean $^{14}CO_2$ inventory between 1945 and 1975 matches the estimated 1975 bomb radiocarbon inventory (Broecker *et al.*, 1995) of 305 x 10^{26} atoms, and the modeled 1975 ocean mean and surface ocean ? $^{14}CO_2$ matches the basin-volume-weighted mean of the natural plus bomb ? $^{14}CO_2$ values measured in the GEOSECS program (Broecker *et al.*, 1985). This tuning yielded a vertical eddy diffusion coefficient is 8,820 m^2 yr^{-1} at the base of the mixed-layer, diminishing with an e-folding length scale of 500 m to a minimum of 2,910 m^2 yr^{-1} at the ocean bottom. The tuned gas transfer velocity is equivalent to 0.0543 mol m^{-2} μatm^{-1} yr^{-1} at 18 °C. More details on the modeling can be found in Caldeira *et al.* (2001).

It should be noted that different ocean models would give somewhat different quantitative results, but they all have a similar overall character (Orr *et al.*, 2000; Caldeira *et al.*, 2002; Wickett *et al.*, in press). This is because all models retain 100% of the injected carbon initially and asymptote at zero long-term net additional carbon storage (relative to atmospheric release) as time approaches infinity; hence, the models differ only in how they transition from the initial state to the final state. For example, after 100 years of simulated injection, all the ocean general circulation models considered by the Ocean Carbon-cycle Model Intercomparison Project (Orr *et al.*, 2000) retained at least 97% of the CO_2 injected at 3000 m, 82-96% of the CO_2 injected at 1500 m, and 73-83% of the CO_2 injection at 800 m. The schematic model considered here retained 99.98%, 95%, and 68%, respectively, for these depths. Therefore, while using different ocean models may change our quantitative results somewhat, they do not affect the results and conclusions we draw concerning how to account for leakage from a storage reservoir.

Simulation Results

The results of the model simulations are shown in Figure 1. The derivative of these curves is essentially the function $A(t)$, so we can easily calculate values for $a(t)$ to use in Equations 4-6. Using a 3% discount rate and carbon price assumptions outlined in the previous section, sequestration efficiencies can be calculated for all cases. For case 3, calculations are made for 5 values of t^*. Results are shown in Table I.

Table I. Calculated Values for Sequestration Effectiveness Using a 3% Discount Rate

Depth	Case 1	Case 2	Case 3a	Case 3b	Case 3c	Case 3d	Case 3e
			t* = 20	t* = 50	t* = 100	t* = 200	t* = 500
500	66.3%	0%	49.0%	36.9%	27.9%	20.2%	12.3%
1000	89.4%	0%	81.5%	69.6%	56.6%	43.0%	27.4%
1500	97.2%	0%	94.9%	89.4%	79.7%	65.4%	44.7%
2000	99.5%	0%	99.0%	97.7%	93.7%	84.3%	63.5%
3000	99.96%	0%	99.9%	99.8%	99.4%	96.8%	83.4%

For case 1, where carbon prices are constant, there is a definite benefit from delaying the carbon emissions. Under this scenario, sequestration in the deep ocean below depths of 1500 m will have essentially the same effect as permanent sequestration.

In case 2, where carbon prices rise at the discount rate, no distinction is made about when CO_2 is emitted. Emitting one ton a thousand years from now will have the same impact as emitting one ton today. Under this scenario, leaky reservoirs are not effective for carbon sequestration as eventually all of the carbon leaks. Permanence is a necessary criterion.

Case 3, where carbon prices rise at the discount rate for t^* years and then remain constant, may be the most realistic scenario and also yields the most interesting results. If a backstop technology can be developed before the carbon stored in the reservoir starts to leak in significant quantities, then the sequestration can be very effective. For example, at a 3000 m injection depth, only 5% leaks out over the first 280 years, so the sequestration effectiveness is very high even at t^*=200 years. On the other hand, at 500 m, 5% leaks out after 5 years making the sequestration effectiveness poor even for a t^*=20 years.

Conventional wisdom has been to inject CO_2 as deep as possible in the ocean to slow its return to the atmosphere (Figure 1). However, the above analysis shows that this simplified view is not a robust conclusion. In fact, the depth of injection very much depends on how one views the price path for carbon emissions. To rigorously calculate optimum injection depths, a calculation of costs versus injection depth is needed in addition to the benefits versus depths shown above. However, rough estimates for target inject depths can be made as follows:

- Case 1 assumptions suggest injection depths of 1500 m.
- Case 2 assumptions imply that non-permanent sequestration is ineffective, so depth is irrelevant.
- Case 3 assumptions indicate that optimal injection depth is related to the time of entry of a backstop technology. Entry in 20 years suggests 1500 m is adequate, while entry in 100 years would want injection depths of at least 2000 m. Injection depths of 3000 m are warranted for entry of a backstop at 200 years.

Table II explores the affect of the discount rate. We varied the discount rate from the base case of 3% to 1%, 5%, and 7% for the 1500 m depth injection. Increasing the discount rate above 3% resulted in only small changes to the sequestration efficiency. However, very significant changes are encountered as the discount rate is lowered and approaches 0%. This is not surprising because at a 0% discount rate, the sequestration effectiveness goes to zero in all cases.

Table II. Sequestration Effectiveness as a Function of Discount Rate for a Depth of 1500 m

DiscRate	Case 1	Case 2	Case 3a	Case 3b	Case 3c	Case 3d	Case 3e
			t* = 20	t* = 50	t* = 100	t* = 200	t* = 500
1%	87.1%	0%	84.3%	79.3%	71.4%	60.0%	42.2%
3%	97.2%	0%	94.9%	89.4%	79.7%	65.4%	44.7%
5%	99.0%	0%	97.3%	92.1%	81.9%	66.8%	45.2%
7%	99.5%	0%	98.3%	93.2%	82.9%	67.5%	45.5%

Conclusions

1. The appropriate formulation to the "permanence" issue as it relates to carbon sequestration is to ask, *"What is the value of temporary storage?"*

2. In practice, a non-permanent CO_2 sequestration reservoir is no different from avoided emissions that are left in the ground as unused fossil fuels. Fossil fuel not used today is still available for use in the future. Permanence or lack thereof of different mitigation options is a function of the policy regime. A policy regime with a permanent global net emissions cap and permanent liability for sequestered carbon will mean that as far as atmospheric concentrations are concerned, reductions are permanent although it may be of economic interest to reverse some reductions and make up for them with other reductions as economic conditions change. If the emissions cap is not global or cannot be maintained in perpetuity, then emissions reductions today will be subject to temporal leakage, similar to a leaky reservoir.

3. Since we considered the value of temporary storage relative to permanent, we could develop a mathematical formulation that depended only on the price path, as opposed to absolute prices. Absolute prices will be required if one wanted to compare the benefits of temporary storage to their costs.

4. Our results show that the value of relatively deep ocean carbon sequestration is nearly equivalent to permanent sequestration if marginal damages (i.e., carbon prices) remain constant or if there is a backstop technology that caps the abatement cost in the not too distant future. There is little value to temporary storage if carbon prices rise at or near the discount rate.

5. The price paths we developed were justified through appeal to the results one would obtain from a dynamic cost-benefit analysis of the climate problem, under different and highly stylized assumptions of climate damages and the availability of mitigation options. The long term and intergenerational aspect of the climate problem poses risks that are not easily removed for future generations and for nearly all mitigation options. A generation or two of shirkers who irresponsibly emitted more carbon from burning fossil fuels after earlier generations had not or who irresponsibly made excess use of leaky reservoirs can impose inequitable costs on future generations.

6. For the specific example of ocean sequestration, many scenarios do not require injection into the deepest ocean. However, deeper injection depths would be required for some of the price paths analyzed.

7. The results are not very sensitive to the discount rate chosen, as long as the discount rate is greater than about 2%. As the discount rate approaches zero, the sequestration effectiveness approaches zero for all cases.

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References

Broecker, W.S., Peng, T-H., Ostlund, H.G., and Stuiver, M.: 1985, 'The distribution of bomb radiocarbon in the ocean', *J. Geophys. Res.*, **90**, pp. 6925-6939.

Broecker, W.S., Sutherland, S., Smithie, W., Peng, T-H., and Ostlund, G.: 1995, 'Oceanic radiocarbon: separation of the bomb and natural components', *Glob. Biogeochem. Cycles*, **9**, pp. 263-288.

Caldeira, K., Herzog, H.J., and Wickett, M.E.: 2001, 'Predicting and evaluating the effectiveness of ocean carbon sequestration by direct injection', Proceedings of First National Conference on Carbon Sequestration, Washington, DC, 14-17 May 2001 (see www.netl.doe.gov).

Caldeira, K., Rau, G.H., and Duffy, P.B.: 1998, 'Predicted net efflux of radiocarbon from the ocean and increase in atmospheric radiocarbon content', *Geophysical Research Letters*, **25**, pp. 3811-3814.

Caldeira, K., Wickett, M.E., and Duffy, P.B.: 2002, '*Depth, radiocarbon and the effectiveness of direct CO_2 injection as an ocean carbon sequestration strategy'. Geophysical Research Letters*, 8 10.1029/2001GL014234.

Dickson, A.E.: 1990 'Thermodynamics of the dissociation of boric acid in syntheic sea water from 273.15 to 298.15 K', *Deep-Sea Research*, **37**, pp. 755-766.

Dubey, M.K., Ziock, H., Rueff, G., Elliott, S., and Smith, W.S.: 2002, 'Extraction of Carbon Dioxide from the Atmosphere through Engineered Chemical Sinkage', *ACS Division of Fuel Chemistry Preprints*, **47**(1), pp.81-84.

Eckaus, R.: 1992, 'Comparing the Effects of Greenhouse Gas Emissions on Global Warming' *Energy Journal*, **13**, pp. 25-34.

Edmonds, J.A., Pitcher, H.M., Barns, D., Baron, R., and Wise, M.A.: 1995, 'Modeling Future Greenhouse Gas Emissions: The Second Generation Model Description', in Klein, L.R. and Fu-Chen, L., (eds.), *Modelling Global Change*, United Nations University Press, Tokyo, Japan, pp. 295-340.

Hansen, J.E., Sato, M., Ruedy R., Lacis, A., and Oinas, V.: 2000, 'Global warming in the 21st century: an alternative scenario', *Proc. of the Nat. Acad. of Sci.*, **97(18)**, pp. 9875-9880.

Herzog, H.J.: 2001, 'What Future for Carbon Capture and Sequestration?', *Environmental Science and Technology*, **35:7**, pp. 148A-153A.

Herzog, H.J., Eliasson, B., and Kaarstad, O.: 2000, 'Capturing Greenhouse Gases', *Scientific American*, **282(2)**, pp. 72-79.

Hotelling, H.: 1931, 'The Economics of Exhaustible Resources', *Journal of Political Economy*, **39**, pp. 137-175.

Kandlikar, M.: 1995, 'The Relative Role of Trace Gas Emissions in Greenhouse Gas Abatement', *Energy Policy*, **23**, pp. 879-883.

Kandlikar, M.: 1996 'Indices for Comparing Greenhouse Gas Emissions: Integrating Science and Economics', *Energy Economics*, **18**, pp. 265-281.

Lind, R.C. and R.E. Schuler: 1998, 'Equity and discounting in climate-change decisions', in Nordhaus, W.D. (ed.), *Economics and Policy Issues in Climate Change*, Resources for the Future, Washington DC, pp. 59-96.

Manne, A. and Richels, R.: 2001 'An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases', *Nature*, **410**, pp. 675-677.

Manne, A. and Richels, R.: 1995, 'Merge: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies', *Energy Policy*, **3(1)**, pp. 182-213.

Marland, G., Fruit, K., and Sedjo, R.: in press, 'Accounting for Sequestered Carbon: The Question of Permanence', *Environmental Science & Policy*.

Millero, F.J.: 1995, 'The carbon dioxide system in the oceans', *Geoch. Cosmch. Acta*, **59**, pp. 661-677.

Noble, I., Apps, M., Houghton, R., Lashof, D., Makundi, W., Murdiyarso, D., Murray, B., Sombroek, W., and Valentini, R., et al.: 2000, 'Implications of different definitions and generic issues', in Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verado, D.J., and Dokkens, D.J. (eds.), *Land Use, Land Use Change, and Forestry*, Cambridge University Press, Cambridge UK, pp. 53-156.

Nordhaus, W.D.: 1979, 'The Efficient Use of Energy Resources', Cowles Foundation Press, New Haven.

Nordhaus, W.D. and Boyer, J.: 2000, 'Warming the World: Economic Models of Global Warming', MIT Press, Cambridge MA.

Oeschger, H., Siegenthaler, U., Schotterer, U., Gugelmann, A.: 1975, 'A box diffusion model to study the carbon dioxide exchange', *natureTellus*, **27**, pp. 168-192.

Orr, J.C., Aumont, O., Kaspner Plattner, A., Fortunat, J., Maier-Reimer, E., Weirig, M-F, Reiner, E., Schlitzer, R., Caldeira, K., and Matear, R.: 2000, 'Ocean CO_2 Sequestration Efficiency from 3-D Ocean Models,' in *Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies*, Williams, D., Durie, B., McMullan, P., Paulson, C., and Smith, A., (eds.), CSIRO Publishing, Collingwood, Australia, pp. 469-474. (available at: http://www.ipsl.jussieu.fr/OCMIP/papers/peer_rev/ghgt5/ghgt5orr.pdf)

Reichle, D., et al.: 1999, 'Carbon Sequestration Research and Development', Report # DOE/SC/FE-1.

Reilly, J., Babiker, M., and Mayer, M.: 2001 (submitted), 'Comparing Greenhouse Gases', *Environmental and Resource Economics*.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A., Wang, C.: 1999 'Multigas Assessment of the Kyoto Protocol', *Nature*, **401**, pp. 549-555.

Reilly, J., et al.: 2001, 'Uncertainty and climate change assessments', *Science*, **293,** pp. 430-433.

Reilly, J. and Richards, K.: 1993, 'Climate Change Damage and the Trace Gas Index Issue', *Environmental and Resource Economics*, **3**, pp. 41-61.

Roy, R.N., Roy, L.N., Vogel, M., Moore, C.P., Pearson, T., Good, C.E., Millero, F.J., and Cambell, D.J.: 1993, 'Determination of the ionization constants of carbonic acid in seawater', *Mar. Chem.*, **44**, pp. 249-268.

Schmalensee, R.: 1993, 'Comparing Greenhouse Gases for Policy Purposes', *Energy Journal*, **14**, pp. 245-255.

Siegenthaler, U.: 1983, 'Uptake of excess CO_2 by an outcrop-diffusion model of the ocean', *J. Geophys. Res*., **27**, pp. 3599-3608.

Smith, J.B., Schellnhuber, H-J., Qader Mirza, M.M., et al.: 2001, 'Vulnerability to Climate Change and Reasons for Concern: A Synthesis', in McCarthy, J., Canziani, O., Leary, N., Dokken, D., and White, K., (eds), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, published for the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp. 913-967.

Stumm, W. and Morgan, J.J.: 1981, 'Aquatic Chemistry', 2nd ed., Wiley-Interscience, New York.

Tol, R.S.J.: 1999, 'The marginal costs of greenhouse gas emissions', *The Energy J*., **20(1)**, pp. 61-82.

Weiss , R.F.: 1974, 'Carbon dioxide in water and seawater: the solubility of a non-ideal gas', *Marine Chemistry*, **2**, pp. 203-215.

Wickett, M.E., Caldeira, K., and Duffy, P.B.: in press, 'High-resolution simulations of oceanic direct-injection of anthropogenic CO_2 and CFC uptake', *Journal of Geophysical Research (Oceans).*

Wigley, T.M.L., Richels, R., and Edmonds, J.A.: 1996, 'Economic and Environmental Choices in the Stabilization of CO_2 Concentrations', *Nature*, **379**, pp. 240-243.

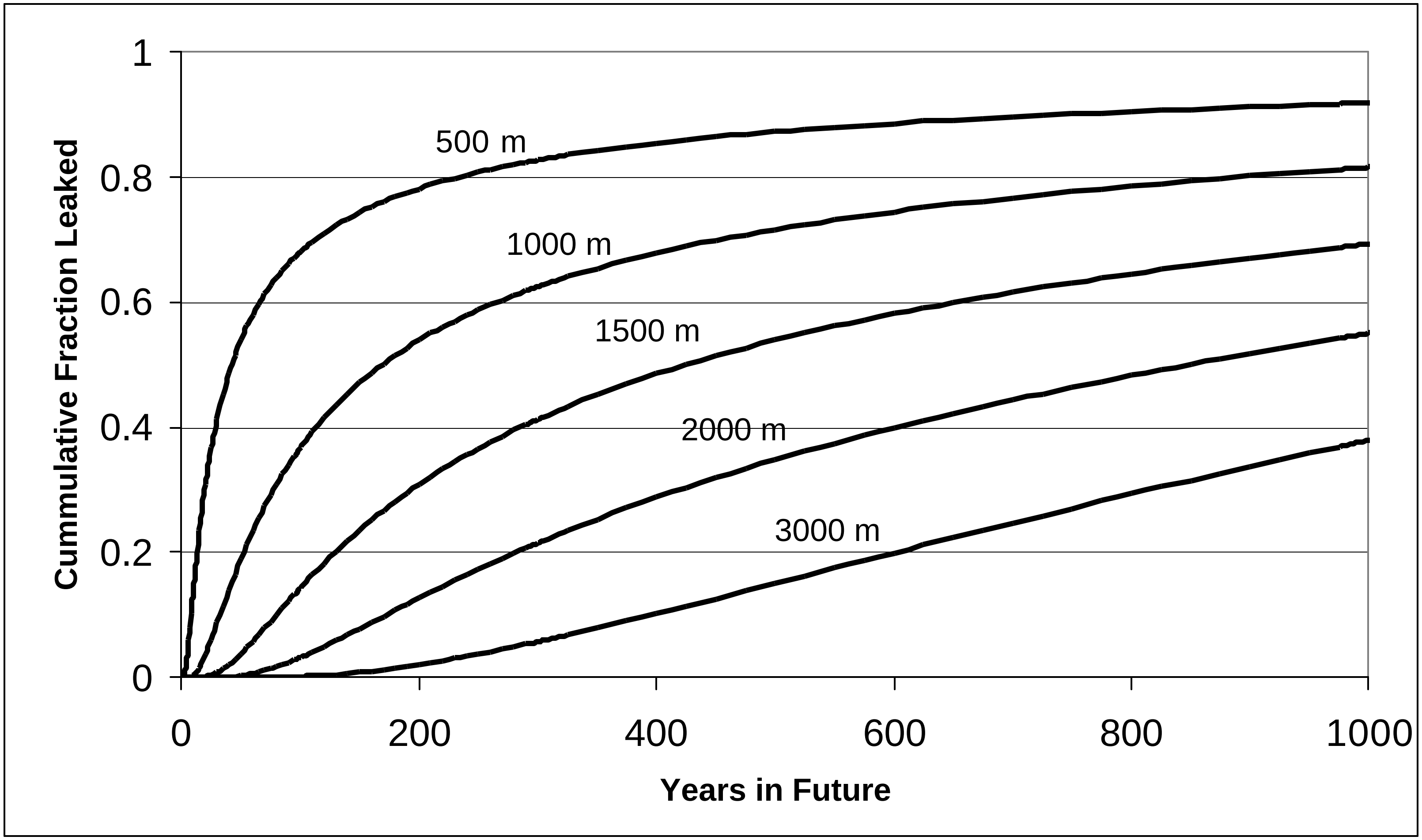

Fig. 1. Leakage over time as a function of injection depth.